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Magnetic Cataclysmic Variables and AM CVn Systems Discovered using the X-ray Main Sequence Applied to SRG/eROSITA Data

Antonio C. Rodriguez* **and Zwicky Transient Facility (ZTF) Variable Star Group**

Department of Astronomy, California Institute of Technology, 1200 E. California Blvd, Pasadena, CA, 91125, USA

E-mail: acrodrig@astro.caltech.edu

Magnetic cataclysmic variables (CVs) are important probes of binary star evolution and accretion in magnetic environments. They consist of a magnetic ($B \approx 1 - 250$ MG) white dwarf (WD) accreting from a Roche lobe-filling late-type star. AM CVns are the ultracompact cousins of CVs, consisting of a white accreting from a Roche lobe-filling helium-rich donor, with orbital periods between 5–65 min. The shortest period AM CVns are strong gravitational wave sources, but only 60–70 systems have been discovered to date. Both Magnetic CVs and AM CVns are luminous X-ray sources, but have been difficult to find in purely optical surveys due to their lack of outburst behavior. Here, I describe the discovery of new systems using a combination optical and X-ray data in a diagram recently dubbed “The X-ray Main Sequence". I present two new magnetic CVs and one new AM CVn discovered in data from the eROSITA telescope aboard the SRG mission, which has carried out the deepest all-sky X-ray survey to date. The diversity of CVs found in this early data suggests that there are many exotic systems to be discovered in the near future.

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*Speaker

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1. Introduction

Compact object binaries are the products of binary star evolution and can be the progenitors of brilliant explosions such as Type Ia supernovae and kilonovae. Magnetic cataclysmic variables (CVs) are compact object binaries in which a highly magnetized white dwarf (WD) accretes from a Roche-lobe filling donor, typically a late-type main-sequence star [1]. Magnetic CVs are interesting for two reasons: 1) they may be the dominant contributors to the X-ray excess from the Galactic Center and Galactic Ridge [2], and 2) the origin of the strong ($B \sim$ 1–250 MG) magnetic fields in accreting WDs is uncertain [3]. They are also rich laboratories for studying accretion under in highly magnetic environments.

AM CVns are ultracompact CVs with orbital periods between 5–65 min [4]. In order to reach such short orbital periods, the Roche lobe-filling donor must be helium-rich. Indeed, AM CVns are characterized by prominent helium lines and the lack of hydrogen lines in optical spectroscopy. Three main formation channels for these systems have been proposed, but it remains unclear which is the dominant one. Moreover, it has proven challenging to precisely characterize the cold donor star using optical data since the WD is so much more luminous in the optical. The discovery of eclipsing AM CVns is particularly important since binary parameters in those systems can be well-constrained [5].

All-sky surveys have been particularly important for the discovery of both magnetic CVs and AM CVns, with *HEAO-1* identifying many of the first magnetic CVs, and later *ROSAT* identifying the first large sample of magnetic CVs and some of the most extreme AM CVns [6, 7]. The eROSITA telescope aboard the Spektr-RG (SRG/eROSITA) observatory has conducted the first all-sky X-ray survey in nearly 30 years [8]. A single SRG/eROSITA scan goes about five times deeper than its predecessor, ROSAT, and its source localization is better by a similar factor[1]. SRG/eROSITA has the potential to make important discoveries in the field of stellar astronomy. Furthermore, we are in the age of precise all-sky astrometry with *Gaia* and thousands of epochs of Northern sky photometric coverage with ZTF[2] [9]. While optical surveys are useful on their own, they contain billions of targets. Such a large dataset is intractable without initial cuts such as an X-ray counterpart.

2. Discovery Tool: The X-ray Main Sequence

2.1 Data

In order to describe the X-ray Main Sequence, the first dataset used in this presentation is the *XMM-Newton/Gaia* crossmatch described in [10]. We began with the Fourth *XMM-Newton* Source Catalog, 13th Edition (4XMM-DR13), which contains 656,997 sources. It is comprised of all publicly available observations taken with the European Photon Imaging Camera (EPIC) in the 0.2–12 keV range between February 13, 2000 and December 31, 2022. Taking overlapping fields into account, this catalog covers ~1328 deg^2 (3%) of the sky. We then crossmatched the cleaned sources from the *XMM-Newton* catalog with *Gaia* Data Release 3 (DR3) within a 2" radius.

[1]The limiting flux of the 2RXS ROSAT catalog is $2 - 3 \times 10^{-13}$erg s^{-1}cm^{-2}, while that of a single eROSITA scan is 5×10^{-14}erg s^{-1}cm^{-2} The mean error circle of ROSAT is 15", but sources are regularly found up to 40" away from the X-ray position [?]. However, mean error circle of eROSITA is 5", with 98% positional uncertainty at 15" [?].

[2]The mean ZTF lightcurve in the latest data release has ~800 epochs of photometric measurements.

After this crossmatch, we selected only for objects that fulfilled the following criteria. The main requirement is that they have no detection flags and are likely Galactic sources:

- Well localized point sources: `SC_EXTENT` = 0 and `CONFUSED` = 0.
- 5σ detections: `SC_DET_ML` > 14.
- Low probability of being a spurious detection: `SC_SUM_FLAG` ≤ 1.
- Significant parallax and proper motions: `parallax_over_error` > 3 and `pm/pm_error` > 5 in both RA and DEC.
- Significant photometry: `phot_mean_flux_over_error` > 3 in all bands.
- Uncontaminated photometry: `phot_bp_rp_excess_factor_corrected` < 0.05.
- Good astrometry: `RUWE` <1.4.

This provided a set of 25,050 sources in the final crossmatch.

We then crossmatched this list to well-vetted catalogs in the literature (including, but not limited to): active stars (including binaries), cataclysmic variables, millisecond pulsar binaries (spiders), symbiotic stars, and X-ray binaries. Further details on this crossmatch and catalogs used are in [10].

2.2 Results

In Figure 1, we show the X-ray Main Sequence as presented in Figure 1 of [10]. The "empirical cut" distinguishes accreting compact objects from active stars, while symbiotic stars seem to occupy their own part of phase space below. To construct this diagram from the *XMM-Newton/Gaia* crossmatch, we plot the Gaia BP–RP color on the horizontal axis: `phot_bp_mean_mag`–`phot_rp_mean_mag`. On the vertical axis, we divide the mean X-ray flux in the 0.2–12 keV band, `SC_EP_8_FLUX`, by the optical flux in the Gaia G band, $10^{0.4(m_\odot - m)} L_\odot/(4\pi(1\ \mathrm{AU})^2)$, where $m_\odot = -26.7$ and m is `phot_g_mean_mag`.

We also place three objects detected in SRG/eROSITA data on the X-ray Main Sequence — in particular, the three systems described later in this work: eFEDSJ0850, eFEDSJ0926, and SRGeJ0453. In brief, we show that the X-ray Main Sequence is a valuable tool for the discovery of accreting compact objects in X-ray + optical crossmatches: it is an easy diagram to construct, and efficiently separates out false positives.

3. Magnetic CVs: Two New Systems in the SRG/eROSITA eFEDS Catalog

3.1 Data

We began with the catalog of eROSITA Final Equatorial Depth Survey (eFEDS) Galactic sources [11]. The "Main" catalog consists of all detections detected in the 0.2–2.3 keV band with a detection likelihood larger than 6, while the "Hard" catalog consists of all sources in the 2.3–5 keV range with a detection likelihood larger than 10. [11] searched for optical counterparts to the

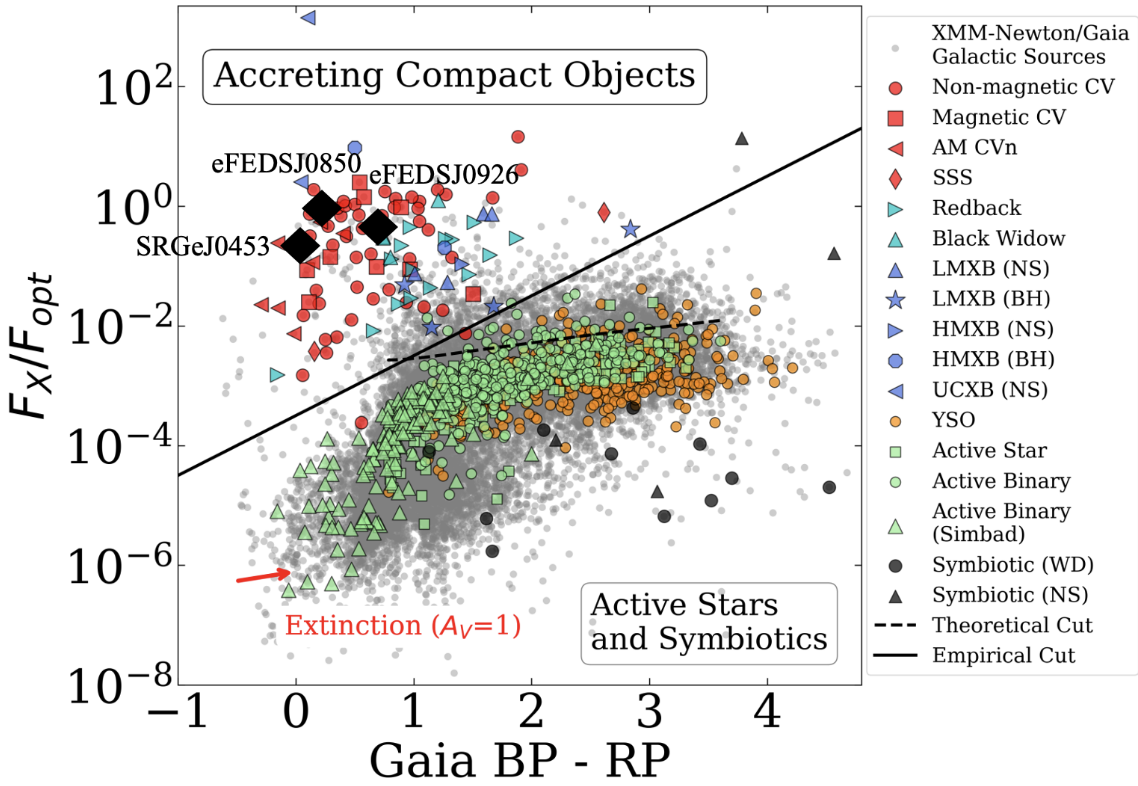

Figure 1: The X-ray Main Sequence as shown in [10]. Accreting compact objects, including the two polars and AM CVn presented in this work, are above the “empirical cut", while active stars are below.

eFEDS X-ray sources by crossmatching to the DECam Legacy Survey (DECaLS) LS8 catalog, part of the DESI Legacy Imaging Survey version DR8. The the mean X-ray positional error (i.e. the eROSITA/SRG uncertainty in the localization of the X-ray source) in the eFEDS catalog is 4".7. The median separation between the X-ray source and optical counterpart, divided by the mean X-ray positional error, is 1.22. For the crossmatch to ZTF data, we use the coordinates of the LS8 optical counterpart. Given the superior depth of DECaLS (23.4 mag), we crossmatch the sources to the LS8 catalog instead of the ZTF catalog (21 mag).

Galactic sources in eFEDS are mainly identified through two methods as described in [11]: 1) SDSS redshifts being $z < 0.002$ and/or 2) *Gaia* parallaxes with good significance: $\pi/\sigma_\pi > 3$. The Renormalised Unit Weight Error (RUWE) < 1.4 can also be used. The actual method described in [11] is complex, and uses a combination of NWAY, a tool based on Bayesian statistics, and ASTROMATCH, a tool based on the Maximum Likelihood Ratio.

In the eFEDS Main Catalog, 24774/27369 (90.5%) of X-ray sources are reported to have a reliable optical counterpart. Of those sources, 2976 are classified with the label `LIKELY GALACTIC` or `SECURE GALACTIC`. It is this sample that we placed on the X-ray Main Sequence. Only 30 of those objects were located in the upper corner, which we labeled as CV candidates. After crossmatching this sample with ZTF and keeping only high-amplitude (> 1 mag) periodic sources (SNR > 10), we were left with two objects: eFEDS J085037.2+044359 (henceforth eFEDSJ0850) and eFEDS J092614.1+010558 (henceforth eFEDSJ0926).

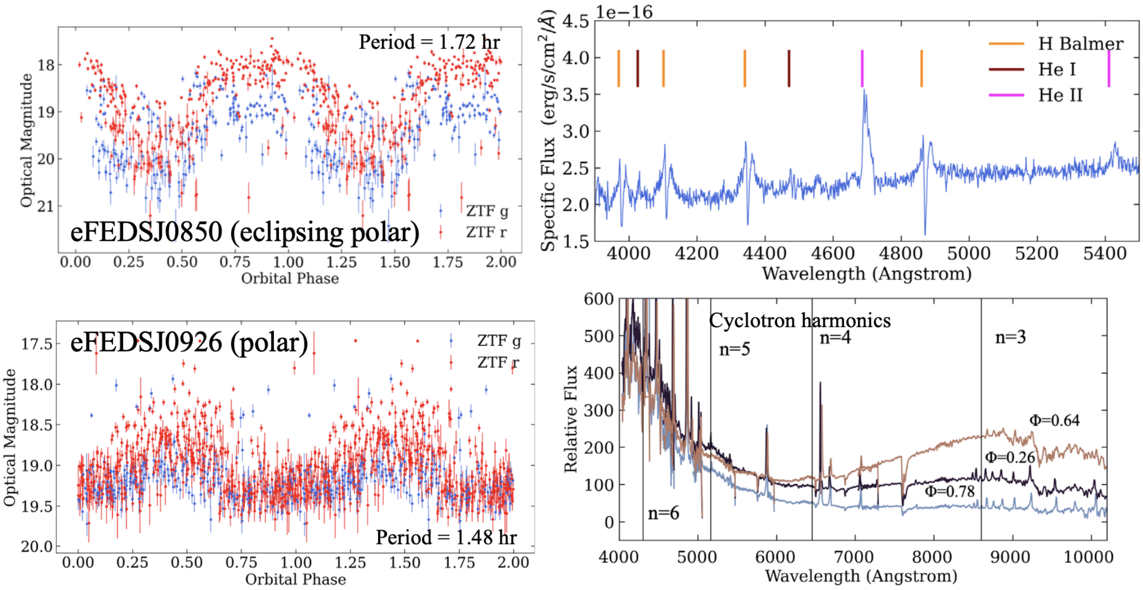

Figure 2: Confirmation of two new polars with in the SRG/eROSITA eFEDS dataset using ZTF photometry and Keck spectroscopy. On the left, high amplitude periodic modulations suggest cyclotron beaming. On the right, strong He II 4686 confirms their magnetic nature. In the case of J0850, Balmer absorption lines suggest the system is eclipsing (which was confirmed by high-speed photometry), and in the case of J0926, cycltron harmonics imply a WD magnetic field strength of 36–42 MG. All figures are adapted from [12].

3.2 Results

In Figure 2, we show the confirmation of eFEDSJ0850 and J0926 as polars. All figures are adapted from [12]. In the case of eFEDSJ0850, the extremely high amplitude modulation (nearly 3 mag peak-to-peak) revealed by ZTF effectively confirms this is a polar, since cycltron beaming is responsible for this light curve behavior. Keck I/LRIS phase-resolved spectroscopy was obtained, and shows strong He II 4686, which confirms the magnetic nature. Furthermore, a high-speed optical light curve (shown in [12]) reveals the system to be eclipsing, which allows for a precise determination of the WD mass and other binary parameters.

In the case of eFEDSJ0926, the ZTF light curve is also sufficient to essentially confirm the polar nature of this object, since the ≈1.5 mag amplitude modulation must be due to cyclotron beaming. Medium-resolution phase-resolved spectra obtained with Keck II/ESI reveal the cyclotron harmonics, which modulate with the orbital period. Using the canonical cyclotron wavelength relation, $\lambda_n = \frac{10710}{n}\left(\frac{100\,\mathrm{MG}}{B}\right)\sin\theta$ Å, reveals that this system should have a WD magnetic field strength between 36–42 MG.

In both cases, the systems are well below the period gap, and the orbital period of eFEDSJ0926 is only about ten minutes above the CV period minimum. Although this is a small sample of objects, the fact that both are below the gap continues to suggest that polars are rarely found above the gap at long ($P > 3$ hr) orbital periods.

4. AM CVn: One New System in SRG/eROSITA

4.1 Data

We obtained access to a private SRG/eROSITA dataset for a small survey of CV candidates covering approximately 600 sq. deg. of the Northern sky. We began with systems in the 0.2–2.3 keV range of eROSITA down to a flux limit of approximately 1×10^{-14} erg/s/cm^2, since we had access to eRASS:4 (4 summed sky surveys). We selected systems that were in the upper left corner of the X-ray Main Sequence and were also near the WD track, in order to optimize for systems that were less likely to have been discovered before. We ended with a list of 10 CV candidates, and obtained spectroscopy for the 8 brightest systems. SRGeJ045359.9+622444 (hereafter, SRGeJ0453) was the first of those systems and optical follow-up data revealed it was important enough to deserve a single-object paper.

4.2 Results

In Figure 3, we show the optical follow-up data for SRGeJ0453, which confirmed it as an AM CVn. All figures are shown in [13]. The ZTF long-term light curve reveals no outbursts, but there was a significant peak in the Box Least Squares (BLS) periodogram at 55.1 minutes. The folded ZTF light curve shows deep eclipses, which were confirmed with optical high-speed photometry taken with the CHIMERA instrument on the 200-inch telescope at Palomar Observatory. Furthermore, the Keck I/LRIS spectrum reveals strong He I and He II emission lines, and a lack of H Balmer lines. Other metal absorption lines are present, which indicate the WD has been polluted by its once metal-rich donor. Finally, modeling the eclipse of the high-speed optical light curve constrains the binary parameters of the system.

5. Discussion: Why is the X-ray Main Sequence Useful?

None of the systems presented here could be found in “traditional" optical-only CV surveys that search for dwarf nova outbursts. While the first two systems could be found through an extensive period search of ZTF data, such a search is expensive and would be subject to false positives. The third system shown here, however, would be extremely difficult to find, even through a light curve period search, since only two points are in eclipse. The major leap here is the advent of the large X-ray catalog from eROSITA, which can be used to construct the X-ray Main Sequence. In Figure 4, we show two different types of CVs: one that can be easily selected in optical-only surveys, and one that can go by essentially undetected. In both cases, the systems are X-ray emitters and can be identified through the X-ray Main Sequence.

6. Conclusion

In this conference proceeding, we have presented the following:

- A new tool, refereed to as the X-ray Main Sequence in [10], which can be used to identify a wider variety of CVs, including non-outbursting and magnetic systems, that can be easily missed in optical surveys. As a proof-of-concept, we presented three systems discovered using this tool.

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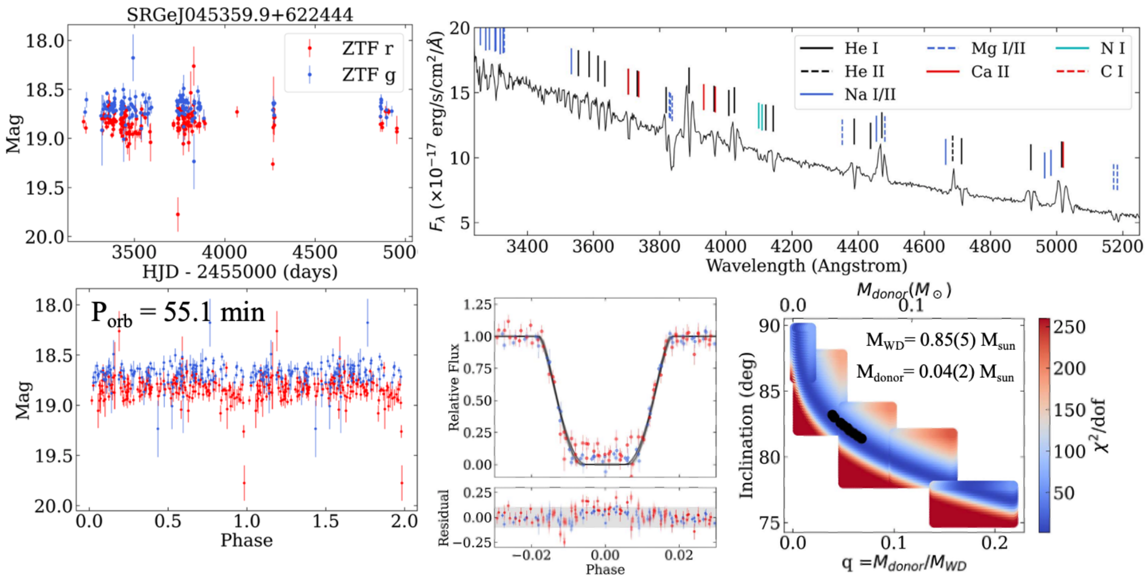

Figure 3: Confirmation of SRGeJ0453 as an eclipsing AM CVn through ZTF photometry, high-speed photometry, and optical spectroscopy. Left: While the long-term ZTF data reveals no outbursts, the folded light curve (at the peak of a BLS periodogram) shows a 55.1 min period with a deep eclipse. Top right: strong helium lines confirm the AM CVn nature of this object. Bottom right: modeling the eclipse of the optical light curve constrains the binary parameters, placing the WD mass in a similar range as that of CVs. All figures are adapted from [13].

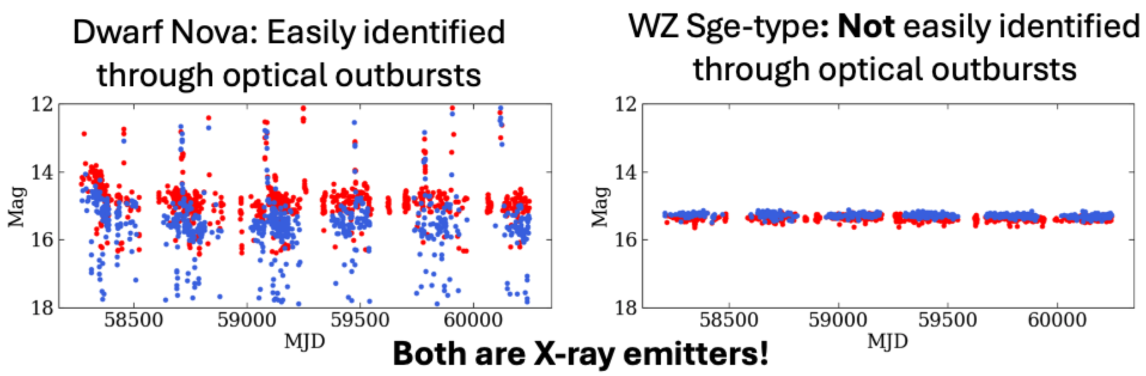

Figure 4: Two nearby CVs are shown, along with their 5-year-long ZTF light curves (g-band in blue, r-band in red): IP Peg (left) and WZ Sge (right). Optical surveys for CVs preferentially find systems through their dwarf nova outbursts, like those seen in IP Peg. However, it is very difficult to find systems like WZ Sge purely through optical data (though WZ Sge was found through an optical outburst, which are infrequent in these low accretion rate systems). Since both systems are X-ray emitters, and are located in the upper left corner of the X-ray Main Sequence (Figure 1), X-ray + optical surveys are necessary for selecting a complete CV population without bias.

- Two new polars discovered with the X-ray Main Sequence in data from the newest all-sky X-ray survey, eROSITA aboard SRG. These two polars in the SRG/eROSITA eFEDS dataset are periodic in optical ZTF data, which constrains their orbital periods to 1.72 and 1.48 hr.
- One new AM CVn also discovered with the X-ray Main Sequence in a private dataset from SRG/eROSITA. This system is almost impossible to detect in purely optical data, and its eclipsing nature allowed us to constrain the binary parameters of the system.

With future releases of X-ray data from SRG/eROSITA on the horizon, as well as optical data from ZTF and soon, the Rubin Observatory Legacy Survey of Space and Time (LSST), the methodology above can be applied for the discovery of more exotic CVs. Ongoing work includes the construction of large samples in order to get a sense of the true CV population in the X-ray sky.

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